

SIDEWALL FUNCTIONALIZATION OF CARBON NANOTUBES WITH HYDROXYL-TERMINATED MOIETIES

[0001] This invention was made with support from the Robert A. Welch Foundation, Grant Number C-0109; and the Texas Higher Education Coordinating Board, ATP Grant Number 003604-0026-2001.

CROSS REFERENCE TO RELATED APPLICATIONS

[0002] This Application claims priority to United States Provisional Patent Application Serial Nos. 60/478,936 and 60/490,556, filed June 16, 2003 and July 28, 2003, respectively. The present Application is related to commonly-assigned Patent Application filed concurrently herewith, entitled, "Fabrication of Carbon Nanotube Reinforced Epoxy Polymer Composites Using Functionalized Carbon Nanotubes," and incorporated by reference herein.

FIELD OF THE INVENTION

[0003] The present invention relates generally to carbon nanotubes, and specifically to methods of functionalizing carbon nanotubes with hydroxyl-terminated moieties.

BACKGROUND

[0004] Carbon nanotubes (CNTs), comprising multiple concentric shells and termed multi-wall carbon nanotubes (MWNTs), were discovered by Iijima in 1991 [Iijima, S. *Nature* 1991, 354, 56]. Subsequent to this discovery, single-wall carbon nanotubes (SWNTs), comprising a single graphene rolled up on itself, were synthesized in an arc-discharge process using carbon electrodes doped with transition metals [Iijima, S.; Ichihashi, T. *Nature* 1993, 363, 603; and Bethune, D.S., Kiang, C.H.; de Vries, M.S.; Gorman, G.; Savoy, R.; Vasquez, J; Beyers, R. *Nature* 1993, 363, 605]. These carbon nanotubes (especially SWNTs) posses unique mechanical, electrical, and thermal properties, and such properties make them attractive for a wide variety of applications.

[0005] Chemical manipulation of single-wall carbon nanotubes (SWNT), especially sidewall functionalization, has recently become an area of escalated fundamental and technological interest. Both covalent and noncovalent sidewall chemistry of SWNTs have been reported, including direct fluorination and subsequent derivatization, addition of radicals, carbenes and nitrenes as well as the 1,3-dipolar and electrophilic additions, and modification through van der Waals interactions with aromatic molecules or polymers. See Khabashesku, V. N.; Margrave, J. L. "Chemistry of Carbon Nanotubes" in *Encyclopedia of Nanoscience and Nanotechnology*, Ed. S. Nalwa, American Scientific Publishers, 2004, Volume 1, pp. 849-861, and references therein; Khabashesku, V. N.; Billups, W.E.; Margrave, J. L. *Acc. Chem. Res.*, 2002, 35, 1087; Bahr, J. L.; Tour, J. M. *J. Mater. Chem.* 2002, 12, 1952. The applications of functionalized SWNTs as reinforcers for fabrication of covalently integrated polymer composites [Barrera, E. V. *JOM*, 2000, 52, 38; Zhu, J.; Kim, J.; Peng, H.; Margrave, J. L.; Khabashesku, V. N.; Barrera, E. V. *Nano Lett.* 2003, 3, 1107; Zhu, J.; Peng, H.; Rodriguez-Macias, F.; Margrave, J. L.; Khabashesku, V. N.; Imam, M.A.; Lozano, K.; Barrera, E. V. *Adv. Funct. Mater.* 2003, in press] and as vehicles for targeted drug delivery have recently been demonstrated. See Pantarotto, D.; Partidos, C. D.; Graff, R.; Hoebeke, J.; Briand, J.-P.; Prato, M.; Bianco, A. *J. Am. Chem. Soc.* 2003, 125, 6160. These studies have confirmed the need for derivatization of the SWNTs with the organic functional groups which can provide a high binding affinity and selectivity through covalent or hydrogen bond formation. They also suggest that for improving the processing, particularly in biomedical applications, the covalent sidewall functionalization with moieties terminated with hydrophilic substituents, such as hydroxyl groups, should be of primary importance.

[0006] Recent experimental studies [Khabashesku, V. N.; Billups, W.E.; Margrave, J. L. *Acc. Chem. Res.*, 2002, 35, 1087] have shown that fluoronanotubes prepared by direct fluorination of SWNTs can be used as a versatile precursors for preparation of sidewall functionalized nanotube derivatives through a nucleophilic substitution of fluorine. A simple method for introducing hydroxyl functionalities to CNTs, and especially SWNTs, utilizing fluorinated carbon nanotubes as intermediates, would be very advantageous, particularly for situations requiring the dispersal of carbon nanotubes in polar solvents.

SUMMARY

[0007] The present invention is directed to methods of forming sidewall-functionalized carbon nanotubes, wherein such functionalized carbon nanotubes have hydroxyl-terminated moieties covalently attached to their sidewalls. Generally, such methods involve chemistry on carbon nanotubes that have first been fluorinated.

[0008] In some embodiments, fluorinated carbon nanotubes ("fluoronanotubes") are reacted with mono-metal salts of a dialcohol, MO-R-OH, where M is a metal and R is hydrocarbon or other organic chain and/or ring structural unit. In such embodiments, -O-R-OH displaces -F on the nanotube, the fluorine leaving as MF. Generally, such mono-metal salts are formed *in situ* by the addition of MOH to one or more dialcohols in which the fluoronotubes have been dispersed.

[0009] In some embodiments, fluoronanotubes are reacted with amino alcohols, such as being of the type H₂N-R-OH, wherein -N(H)-R-OH displaces -F on the nanotube, the fluorine leaving as HF.

[0010] In some embodiments, variations of the above-described chemistries are employed in which thiol groups, -SH, replace one or both of the -OH groups in the dialcohols, and/or the -OH group in the amino alcohol.

[0011] Applications for such nanotubes functionalized with hydroxyl-terminated moieties are far reaching, but many will undoubtedly capitalize on their enhanced dispersability and/or solubility in polar solvents and further functionalization that can be carried out with the terminal hydroxyl group. As an example, the hydroxyl-terminated moieties on the carbon nanotubes can be reacted with epichlorohydrin to yield carbon nanotubes with epoxide groups attached to their sidewalls. These epoxide-functionalized carbon nanotubes can be mixed with epoxy resins and cured with an appropriate curing agent to form carbon nanotube-epoxy composites.

[0012] The foregoing has outlined rather broadly the features of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter which form the subject of the claims of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0014] FIGURE 1 depicts Raman spectra of SWNT materials: fluoronanotube 1 (A), hydroxyl-nanotubes 3a (B), 3b (C), and residue after TGA of 3b;

[0015] FIGURE 2 depicts Raman spectra of hydroxyl-nanotubes: (A) 3c, (B) 3d, (C) 3e, (D) 3f;

[0016] FIGURE 3 depicts Raman spectra of SWNT materials: (A) 3g, (B) residue after TGA of 3g, (C) 3h, (D) 3l; and

[0017] FIGURE 4 depicts UV-vis-NIR spectra of pristine SWNTs (A), fluoronanotubes 1 (B), and hydroxyl-nanotubes 3f (C) and 3g (D);

[0018] FIGURE 5 depicts ATR-FTIR spectra of fluoronanotube 1 (A) and hydroxyl-nanotubes (B) 3a, (C) 3b, (D) 3c, (E) 3d, (F) 3e, (G) 3f;

[0019] FIGURE 6 depicts ATR-FTIR spectra of hydroxyl-nanotubes: (A) 3g, (B) 3h, (C) 3l;

[0020] FIGURE 7 depicts TGA-DTA of hydroxyl-nanotubes 3b;

[0021] FIGURE 8 depicts TGA-DTA of hydroxyl-nanotubes 3f;

[0022] FIGURE 9 depicts TGA-DTA of hydroxyl-nanotubes 3g;

[0023] FIGURE 10 depicts a TEM image of a specimen of hydroxyl-nanotubes 3f wherein the inset depicts a zoomed-in image of a single functionalized nanotube;

[0024] FIGURE 11 depicts an AFM image and a height analysis along a backbone of a bundle of hydroxyl-nanotubes 3f, wherein the arrows point to a 0.8 nm height difference due to sidewall functionalization; and

[0025] FIGURE 12 depicts a photograph of SWNT materials dispersion in ethanol: (A) pristine SWNTs, and (B) glycerol-functionalized SWNTs 3f.

DETAILED DESCRIPTION

[0026] The present invention is directed to methods of forming sidewall-functionalized carbon nanotubes, wherein such functionalized carbon nanotubes

have hydroxyl-terminated moieties covalently attached to their sidewalls ("hydroxyl-nanotubes"), and to the compositions and articles of manufacture made by such methods. Generally, such methods involve chemistry on carbon nanotubes that have first been fluorinated. While the making and/or using of various embodiments of the present invention are discussed below, it should be appreciated that the present invention provides many applicable inventive concepts that may be embodied in a variety of specific contexts. The specific embodiments discussed herein are merely illustrative of specific ways to make and/or use the invention and are not intended to delimit the scope of the invention.

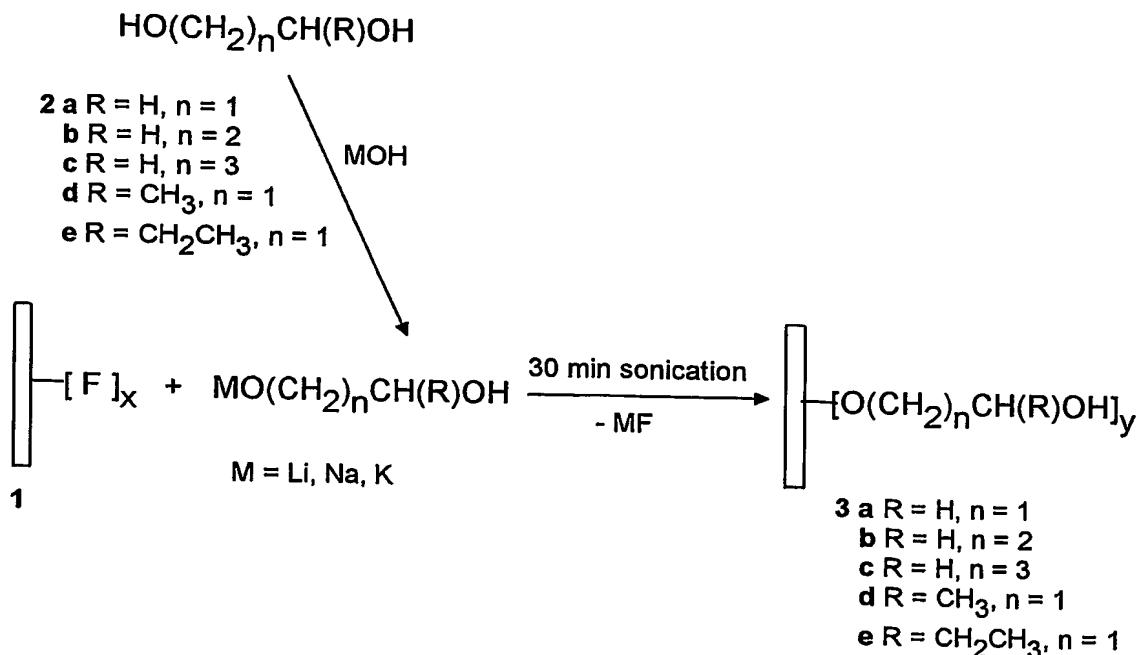
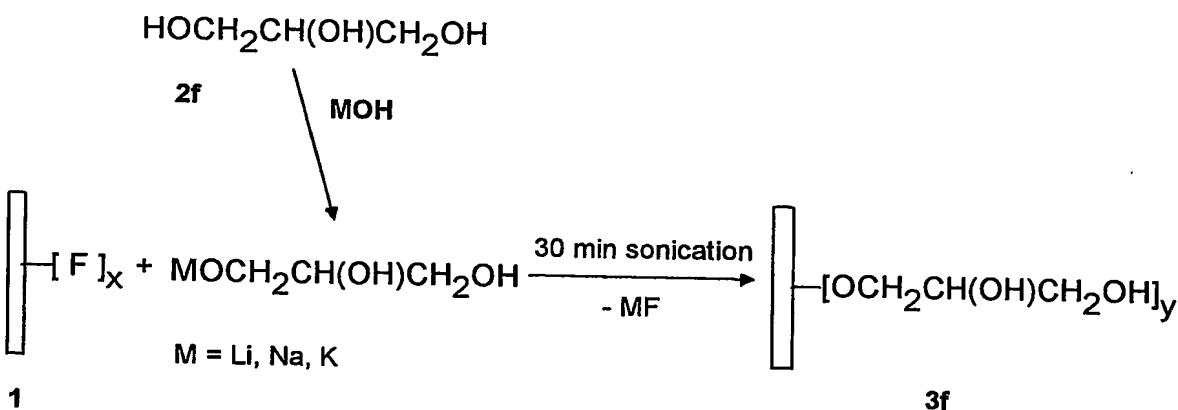
[0027] Carbon nanotubes (CNTs), according to the present invention, include, but are not limited to, single-wall carbon nanotubes (SWNTs), multi-wall carbon nanotubes (MWNTs), double-wall carbon nanotubes, buckytubes, fullerene tubes, tubular fullerenes, graphite fibrils, and combinations thereof. Such carbon nanotubes can be made by any known technique including, but not limited to, arc discharge [Ebbesen, *Annu. Rev. Mater. Sci.* **1994**, 24, 235-264], laser oven [Thess et al., *Science* **1996**, 273, 483-487], flame synthesis [Vander Wal et al., *Chem. Phys. Lett.* **2001**, 349, 178-184], chemical vapor deposition [United States Patent No. 5,374,415], wherein a supported [Hafner et al., *Chem. Phys. Lett.* **1998**, 296, 195-202] or an unsupported [Cheng et al., *Chem. Phys. Lett.* **1998**, 289, 602-610; Nikolaev et al., *Chem. Phys. Lett.* **1999**, 313, 91-97] metal catalyst may also be used, and combinations thereof. Depending on the embodiment, the CNTs can be subjected to one or more processing steps prior to fluorinating them or subjecting them to any of the chemistries of the present invention. In some embodiments, the CNTs are separated based on a property selected from the group consisting of chirality, electrical conductivity, thermal conductivity, diameter, length, number of walls, and combinations thereof. See O'Connell et al., *Science* **2002**, 297, 593-596; Bachilo et al., *Science* **2002**, 298, 2361-2366; Strano et al., *Science* **2003**, 301, 1519-1522. In some embodiments, the CNTs have been purified. Exemplary purification techniques include, but are not limited to, those by Chiang et al. [Chiang et al., *J. Phys. Chem. B* **2001**, 105, 1157-1161; Chiang et al., *J. Phys. Chem. B* **2001**, 105, 8297-8301]. In some embodiments, the CNTs have been cut by a cutting process. See Liu et al., *Science* **1998**, 280, 1253-1256; Gu et al., *Nano Lett.* **2002**, 2(9), 1009-1013. The terms "CNT" and "nanotube" are used synonymously herein.

[0028] In some embodiments, fluorinated carbon nanotubes ("fluoronanotubes"), generally comprising a stoichiometry of about $C_1F_{0.01}$ to about C_1F_1 , are reacted with mono-metal salts of a dialcohol, $MO-R-OH$, where M is a metal and R is hydrocarbon (e.g., $-(CH_2)_n-$) or other organic chain and/or ring structural unit. In such embodiments, $-O-R-OH$ displaces $-F$ on the nanotube, the fluorine leaving as MF . Generally, such mono-metal salts are formed *in situ* by the addition of MOH to one or more dialcohols in which the fluoronotubes have been dispersed.

[0029] The above-described reactions generally require a reaction duration that ranges from about 0.5 hours to about 3 hours. In some embodiments, the reaction is heated with a heating means. In some embodiments, ultrasonication is used to disperse the nanotubes and/or facilitate the reaction. In some embodiments, the reaction is homogenized or mixed using a homogenizing means. Suitable homogenizing means include, but are not limited to, mechanical stirring.

[0030] The dialcohols can be any dialcohol in which fluoronanotubes can be dispersed, and with which the fluoronanotubes will react under appropriate conditions. Some exemplary chemical routes utilizing exemplary dialcohols are shown in Scheme 1 A, wherein fluoronanotube 1 reacts with a mono-metal salt of a dialcohol generated by reacting any of dialcohols 2a-e with MOH , where M equals any of Li, Na, or K, to yield any of functionalized products 3a-e. Other exemplary dialcohols include bis-phenol A.

[0031] The above chemistry can be extended to multi-alcohols as well, as shown in Scheme 1 B, wherein fluoronanotube 1 reacts with a mono-metal salt of a multi-alcohol $R(OH)_n$ generated by reacting multi-alcohols 2f with MOH , where M equals any of Li, Na, or K, to yield functionalized products 3f. Thus, the above description can be extended to reacting fluoronanotubes with any mono-metal salt of the general formula $MOR(OH)_{n-1}$. Again, R is any hydrocarbon or other organic chain and/or ring structural unit that can serve as a backbone for the functionalizing moieties.

Scheme 1**(A)****(B)**

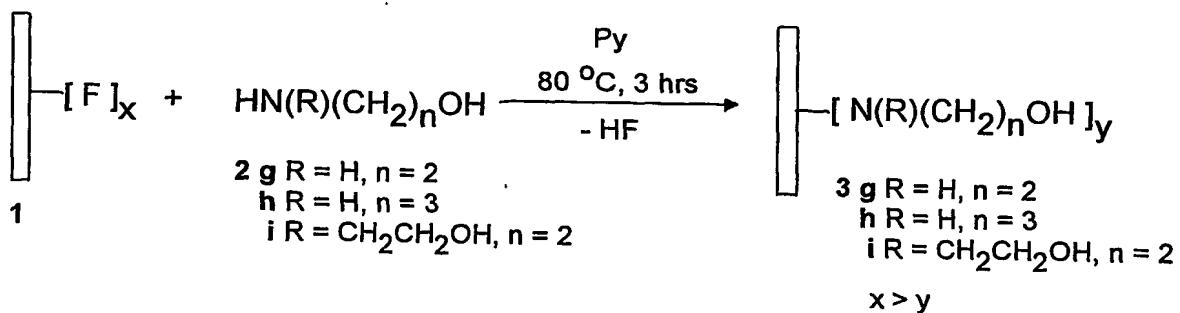
[0032] In some embodiments, the fluoronanotubes are first dispersed in a di- or multi-alcohol to form a dispersion. A metal hydroxide is then dissolved in the same or different di- or multi-alcohol to form a solution, after which the solution and the dispersion are combined to form a mixture. As above, ultrasonication may be employed to facilitate the dispersion formation and/or the mixing step.

[0033] In some embodiments, fluoronanotubes are reacted with amino alcohols, such as being of the type $\text{H}_2\text{N}-\text{R}-\text{OH}$, wherein $-\text{N}(\text{H})-\text{R}-\text{OH}$ displaces $-\text{F}$ on the

nanotube, the fluorine leaving as HF. Generally, in such embodiments, fluoronanotubes are dispersed in an appropriate amino alcohol to form a reaction mixture; a pyridine catalyst is added to the reaction mixture; and the reaction mixture + catalyst is allowed to react to form functionalized carbon nanotubes with amino (amine) terminated moieties. In some embodiments, ultrasonication is used to facilitate dispersion of the fluoronanotubes and/or induce mixing. In these or other embodiments, alternative mixing operations may be employed. Reactions generally take place for a duration that ranges from about 1 hour to about 5 hours, and at a temperature that ranges from about 70°C to about 150°C.

[0034] The amino alcohols can be any amino alcohol in which fluoronanotubes can be dispersed, and with which the fluoronanotubes will react under appropriate conditions. Some exemplary chemical routes utilizing exemplary amino alcohols are shown in Scheme 2, wherein fluoronanotube **1** reacts with amino alcohols **2 g-I** to form functionalized carbon nanotubes **3 g-I** with amino-terminated moieties attached to their sidewalls.

Scheme 2



[0035] In some embodiments, the methods of the present invention are carried out, at least in part, in an inert atmosphere. Such inert atmospheres include, but are not limited to, Ar, Kr, He, Ne, N₂, CF₄, and combinations thereof.

[0036] The above-described methods yield hydroxy-nanotube products. In some embodiments, the hydroxy-nanotube products have a general formula CNT-[OR(OH)_m]_x, where R is a suitable organic backbone, m is at least one, and x is from about 1 to about 500 per 1,000 nanotube carbon atoms. In other embodiments, the

hydroxy-nanotube products have a general formula CNT-[N(Y)R(OH)_m]_x, where R is a suitable organic backbone, Y is hydrogen or other organic species, m is at least one, and x is from about 1 to about 500 per 1,000 nanotube carbon atoms.

[0037] In some embodiments, variations of the above-described chemistries are employed in which thiol groups, -SH, replace one or both of the -OH groups in the dialcohols, and/or the -OH group in the amino alcohol.

[0038] While not intending to be bound by theory, recent DFT calculations [Kudin, K. N.; Bettinger, H. F.; Scusseria, G. E. *Phys. Rev. B*, **2001**, 63, 45413] suggest that fluoronanotubes are better electron acceptors than the naked carbon nanotubes, and therefore might interact readily with strong nucleophilic reagents. These reactions are also facilitated by the weakened C-F bonds in fluoronanotubes (relative to alkyl fluorides), and therefore allowing fluorine to be more easily displaced. The solubility of fluoronanotubes in alcohols has prompted efforts to functionalize them by reactions with alkoxides. In a single example of this reaction documented prior to the present work, sonication of the fluoronanotubes (~ C₂F) in methanol solution of sodium methoxide for 2 hrs was shown to produce the sidewall methoxylated SWNTs with the stoichiometry of C_{4.4}F(OCH₃)_{0.25}. Infrared spectroscopic and variable temperature-mass spectrometry (VTP-MS) data, as well as elevated oxygen content from electron microprobe analysis, confirmed the partial substitution of fluorine in fluoronanotubes and bonding of the methoxy groups to the nanotube sidewalls. See Mickelson, E. T. *Novel Chemistry of Elemental Carbon: Graphite, Fullerenes and Nanotubes*. Ph. D. Thesis, Rice University, Houston, TX, 1999; Mickelson, E. T.; Chiang, I. W.; Zimmerman, J. L.; Boul, P. J.; Lozano, J.; Liu, J.; Smalley, R. E.; Hauge, R. H.; Margrave, J. L. *J. Phys. Chem. B*, **1999**, 103, 4318. It is important to note, however, that sonication or refluxing of fluoronanotubes in alcohols (methanol, ethanol, iso-propanol, ethane diol and glycerol) alone does not result in any significant substitution or elimination of fluorine. See Shukla, R.; McClain, B.; Khabashesku, V. N.; Margrave, J. L. *Rice Quantum Institute 15th Annual Summer Research Colloquium*. Aug.17, 2001, Abstr. p. 19. Therefore, alcohol species (i.e., diols and glycerol) can be used as both solvent media and as reagents to provide a surplus of hydroxyl terminated monoalkoxides through reactions with alkali bases (Scheme 1).

[0039] In previous work, it has been demonstrated that terminal diamines, e.g., $\text{H}_2\text{N}(\text{CH}_2)_n\text{NH}_2$ ($n=2,3,4,6$), can dissolve fluoronanotubes, and, under elevated temperatures (90-150°C), chemically react with them in the presence of catalytic amounts of pyridine. The reactions resulted in an almost complete removal and substitution of fluorine and produced amino group-terminated functionalized SWNTs by creating direct C-N bonding attachments to the sidewalls. See Stevens, J. L.; Kiny, V. U.; Huang, A. Y.; Chiang, I. W.; Derrien, G. A.; Khabashesku, V. N.; Margrave, J. L. *Proc. NanoTech 2003*, Vol. 3, 169-172; Huang, A. Y.; Chiang, I. W.; Khabashesku, V. N.; Margrave, J. L. *Rice Quantum Institute 15th Annual Summer Research Colloquium*. Aug. 17, 2001, Abstr. p. 18; Stevens, J. L.; Huang, A. Y.; Peng, H.; Chiang, I. W.; Khabashesku, V. N.; Margrave, J. L. *NanoLett. 2003*, 3, 331; and Commonly-assigned United States Patent Application Serial No. 10/714,187, filed Nov. 14, 2003.

[0040] Applications for such nanotubes functionalized with hydroxyl-terminated moieties are far reaching, but many will undoubtedly capitalize on their enhanced dispersability and/or solubility in polar solvents and further functionalization that can be carried out with the terminal hydroxyl group. As an example, the hydroxyl-terminated moieties on the carbon nanotubes can be reacted with epichlorohydrin to yield carbon nanotubes with epoxide groups attached to their sidewalls. These epoxide-functionalized carbon nanotubes can be mixed with epoxy resins and cured with an appropriate curing agent to form carbon nanotube-epoxy composites.

[0041] As described above, Applicants have developed convenient and efficient methods for sidewall functionalization of carbon nanotubes with -OH group-terminated moieties, dubbed "hydroxyl-nanotubes". These functional groups have been attached to the nanotube sidewalls through either C-O or C-N covalent bonds (where C is a carbon native to the nanotubes). Such methods are illustrated in Schemes 1 and 2 and utilize mild reaction conditions that can be readily followed. The applications of functionalized carbon nanotubes so prepared may be based on hydrogen bonding ability and chemical reactivity of terminal hydroxyl groups in the side chain. The chemistry of OH group is so abundant that the hydroxyl nanotubes can be used to produce covalently integrated nanotube-reinforced co-polymers and ceramics as well as biomaterials.

[0042] The following examples are provided to more fully illustrate some of the embodiments of the present invention. It should be appreciated by those of skill in the art that the techniques disclosed in the examples which follow represent techniques discovered by the inventors to function well in the practice of the invention, and thus can be considered to constitute exemplary modes for its practice. However, those of skill in the art should, in light of the present disclosure, appreciate that many changes can be made in the specific embodiments that are disclosed and still obtain a like or similar result without departing from the spirit and scope of the invention.

Example 1

[0043] This Example serves to illustrate the types of materials that can be used and how a type of fluoronanotube can be prepared for use in some embodiments of the present invention. Note that while SWNTs were used in this Example, other types of CNTs could be used to make the fluoronanotubes.

[0044] In this Example, raw SWNTs, prepared at Rice University in the Carbon Nanotechnology Laboratory by the HiPco process, have been thoroughly purified to remove iron and other impurities as described previously. See Chiang, I. W.; Brinson, B. E.; Huang, A.Y; Willis, P. A.; Bronikowski, M. J.; Margrave, J. L.; Smalley, R.E.; Hauge, R.H. *J. Phys. Chem. B*, **2001**, 105, 8297. After purification the iron content in the SWNTs did not exceed 1 wt.%. Purified SWNTs, such as that supplied by Carbon Nanotechnologies Inc., Houston, TX, in a powder form, can also be used. The fluoronanotubes **1** of approximately C_{2.5}F stoichiometry have been prepared, in this Example, by direct fluorination of purified SWNTs at 150°C according to the procedure earlier reported by our groups. See Mickelson, E.T.; Huffman, C.B.; Rinzler, A.G.; Smalley, R.E.; Hauge, R.H.; Margrave, J. L. *Chem. Phys. Lett.* **1998**, 296, 188. All other chemicals, such as alcohols **2a-f** and amino alcohols **2g-i**, used in further processing steps to produce hydroxyl-nanotubes, were purchased from Aldrich Chemical Co., Milwaukee, WI.

Example 2

[0045] This Example serves to illustrate the synthetic procedures for methods of the present invention that correspond to Scheme 1.

[0046] For preparation of hydroxyl-nanotubes by this method (Scheme 1), 10-15 mg of fluoronanotubes **1** were placed in a vial with 10 ml of corresponding diols or triols **2a-f** and sonicated (17W/55 kHz Cole Palmer bath) for 30 min at 80-90°C in order to achieve a complete dispersion. In a separate vial, 60-80 mg of LiOH (or NaOH or KOH) was sonicated for 30 min in 10ml of corresponding alkanol until complete dissolution. In the case of diols **2a-h**, this procedure was carried out at room temperature, while in the case of more viscous glycerol **2f**, sonication at elevated temperature (80-90°C) was necessary. In the next step, the solutions from both vials were combined and the resulting mixture sonicated for about 1 hour. The reaction mixture was then filtered through a 1-micron pore size Cole Palmer TEFLON membrane and washed with a large amount of ethanol and water to assure complete removal of LiF (or NaF or KF) and LiOH (or NaOH or KOH) byproducts. The precipitated product, adherring to the membrane as a black-colored film of hydroxyl-nanotubes **3a-f** was peeled off and dried overnight in vacuum oven at 70°C. Energy dispersive analysis of X-rays (EDAX) elemental analyses showed 3-5 at. % residual fluorine content in the samples of **3a-f** derivatives.

Example 3

[0047] This Example serves to illustrate the synthetic procedures for methods of the present invention that correspond to Scheme 2.

[0048] In this Example (Scheme 2) fluoronanotubes **1** (10-15mg) were sonicated in 30ml of amino alcohols **2g-i** for 3 min. This resulted in complete dispersion of fluoronanotubes to form a black colored solution. Thereafter, five drops of pyridine (Py) were added to the solution as a catalyst and the reaction mixture was stirred under a nitrogen atmosphere for three hours at 80-90°C. The reaction mixture was then filtered through a 1-micron pore size Cole Palmer TEFLON membrane with a large amount of ethanol to assure complete removal of unreacted amino alcohol and undesired reaction byproducts. Functionalized SWNTs **3g-i** were removed from the filter membrane and dried overnight in a vacuum oven at 70°C. EDAX analysis revealed residual fluorine content in **3g-i** to be 11-13 at. %.

Example 4

[0049] This Example serves to illustrate how the product produced by the above-described methods can be characterized.

[0050] Raman, attenuated total reflectance-Fourier transform infrared (ATR-FTIR), and ultraviolet-visible-near infrared (UV-vis-NIR) spectroscopies, thermal gravimetric analysis/differential thermal analysis (TGA/DTA), scanning electron microscopy/energy dispersive analysis of X-rays (SEM/EDAX), atomic force microscopy (AFM) and transmission electron microscopy (TEM) methods were all used for characterization of pristine SWNTs, fluoronanotubes, and hydroxyl-nanotubes 3a-i prepared in Examples 2 and 3. The Raman spectra for the samples placed on the top of a standard microscope slide were collected with a Renishaw 1000 microraman system operating with an AlGaAs diode 780-nm laser source. For the ATR-FTIR spectral measurements, a Thermal Nicolet Nexus 870 FTIR system with an ATR accessory was employed. The spectra in the UV-vis-NIR range were taken using a Shimadzu 3101 PC UV/vis/NIR spectrometer. The thermal degradation analyses were performed with a TA-SDT-2960 TGA/DTA analyzer. Scanning electron microscopy (SEM) was performed at 30 kV beam energy using a Phillips XL-30 field emission microscope equipped with an energy dispersive X-ray (EDAX) analyzer. A Digital Instruments MultiMode scanning probe microscope (SPM) with a model 2570JV-Z scanner was used for tapping mode atomic force microscopy analysis (AFM). Transmission electron microscopy (TEM) photoimages of specimen placed on lacey carbon coated copper grids (size 200 mesh) were obtained with a JEOL JEM-2010 electron microscope operating at an accelerating voltage of 100 kV.

a. Optical Spectroscopy

[0051] Raman spectroscopy provides a quick evaluation of the covalent sidewall modification of the nanotubes. The Raman spectra collected for the SWNT derivatives of Examples 2 and 3 are shown on FIGURES 1-3. The observation of the peak in the 1285-1300 cm^{-1} region has been related to the sp^3 states of carbon and is normally used as a proof of the disruption of the aromatic system of π -electrons on the nanotube sidewalls by the attached functional groups. In the Raman spectra of fluoronanotubes 1 (Figure 1A) the observed high-intensity peak at 1293 cm^{-1} reflects the largest content of sp^3 -hybridized sidewall carbons (~ 40%) among all the functionalized SWNTs prepared in Examples 2 and 3. This high degree of sidewall modification in 1 causes the complete disappearance of the SWNT breathing mode peaks seen in pristine SWNTs at 200-260 cm^{-1} , as well as

the broadening and weakening of the tangential mode peak which is red-shifted from 1594 cm⁻¹ in naked nanotubes to 1584 cm⁻¹ in 1. Observed in the Raman spectra of hydroxyl nanotubes 3a-I, the sp³ carbon peaks in the range of 1287-1293 cm⁻¹ thus indicate covalent functionalization. Lower relative intensity of these peaks compared to Raman spectrum of fluoronanotubes 1 can be explained by the ongoing (along with fluorine substitution) sidewall elimination of fluorine from 1 in the reactions studied (Schemes 1,2) which reduces the number of sp³ carbon states and partially restores the sp²-bonding on the nanotube sidewall. Unlike 1, the breathing mode peaks at 200-260 cm⁻¹ become visible in the spectra of 3a-i and exhibit higher intensities for SWNT derivatives 3a and 3d, functionalized at a lowest degree (Figures 1B and 2F). This mode become weaker in derivatives 3b,c,e-i that possess more sidewall-attached groups—which very likely hinder the radial breathing oscillation of the nanotube. See Khabashesku, V. N.; Margrave, J. L. *Chemistry of Carbon Nanotubes* in *Encyclopedia of Nanoscience and Nanotechnology*, Ed. S. Nalwa, American Scientific Publishers, 2004, Vol. 1, pp. 849-861, and references therein; Khabashesku, V. N.; Billups, W.E.; Margrave, J. L. *Acc. Chem. Res.*, 2002, 35, 1087; Bahr, J. L.; Tour, J. M. *J. Mater. Chem.* 2002, 12, 1952.

[0052] UV-vis-NIR spectroscopy serves as another spectroscopic probing of the SWNT sidewall functionalization. In this case, an altering of the electronic structure leads to loss of the van Hove transition features routinely observed in the spectra of pristine nanotubes. In the present Example, this argument is illustrated by comparing in FIGURE 4 the UV-vis-NIR spectra of pristine SWNT with those taken for fluoronanotube 1 and hydroxyl-nanotubes 3f,g in dimethylformamide (DMF) solution. Unlike with naked (e.g., pristine) SWNTs, van Hove singularities are completely absent in the spectrum of the highly functionalized derivative 1. Dramatic reduction in the intensities of van Hove singularities observed for 3f,g made their UV-vis-NIR spectra appear typical for sidewall functionalized SWNTs, thus providing important evidence for the occurrence of chemical modification. See Khabashesku, V. N.; Margrave, J. L. *Chemistry of Carbon Nanotubes* in *Encyclopedia of Nanoscience and Nanotechnology*, Ed. S. Nalwa, American Scientific Publishers, 2004, Vol. 1, pp. 849-861, and references therein; Khabashesku, V. N.; Billups, W.E.; Margrave, J. L. *Acc. Chem. Res.*, 2002, 35, 1087; Bahr, J. L.; Tour, J. M. *J. Mater. Chem.* 2002, 12, 1952; Stevens, J. L.; Kiny, V. U.;

Huang, A. Y.; Chiang, I. W.; Derrien, G. A.; Khabashesku, V. N.; Margrave, J. L. *Proc. NanoTech 2003*, Vol. 3, 169-172.

[0053] The ATR-FTIR spectra shown on FIGURES 5 and 6 were used to identify the hydroxyl group terminated moieties, covalently bonded to the sidewalls of the SWNTs. The strong peak around 1140 cm⁻¹, characteristic of the C-F bond stretches in the fluoronanotubes 1 (FIGURE 5A), has disappeared after reactions with diols, triols, and amino alcohols. This peak was replaced in the spectra of hydroxyl-nanotubes 3a-i by peaks in the 1020-1070 cm⁻¹ region which are attributed to the C-O bond stretches of the nanotube-O-C and C-OH units. The new, very broad bands in the range of 3000-3600 cm⁻¹ are assigned to the O-H stretches, while the peaks in the 2800-3000 cm⁻¹ and 1360-1460 cm⁻¹ regions are assigned to the C-H stretching and deformation modes, respectively. The C-N stretching modes of the nanotube-N(H)-C or nanotube-N(C)-C structural units in derivatives 3g,h and 3i, were observed in the spectral range of 1120-1210 cm⁻¹ (FIGURES 6A-C), characteristic for the C-N modes in secondary and tertiary amines, respectively. See Lin-Vien, D.; Colthup, N. B.; Fateley, W. G.; Grasselli, J. G. *The Handbook of Infrared and Raman Characteristic Frequencies of Organic Molecules*; Academic Press Inc.: San Diego, CA, 1991, p. 299. The activated C=C stretching mode peaks in 1 and 3a-i were observed in the 1540-1580 cm⁻¹ region.

b. Thermal Degradation Studies

[0054] These studies provided further evidence for covalent sidewall derivatization of nanotubes. The TGA-DTA data plots obtained for samples 3b, 3f and 3g (FIGURES 7-9) show on a derivative plots a major peak at 250°C. The appearance of these peaks at such high temperatures indicates that the weight loss is caused by detachment and fragmentation of OH group-terminated moieties and not by the desorption of physisorbed species from nanotubes. The second peak observed on DTA plots for these SWNT derivatives at about 550°C is due to elimination of residual C-F bonds [Khabashesku, V. N.; Billups, W.E.; Margrave, J. L. *Acc. Chem. Res.*, 2002, 35, 1087; Mickelson, E. T. *Novel Chemistry of Elemental Carbon: Graphite, Fullerenes and Nanotubes*. Ph. D. Thesis, Rice University, Houston, TX, 1999], correlating with the EDAX-measured residual fluorine content. The minor character of these peaks shows that the majority of the C-F bonds in

fluoronanotubes **1** have been efficiently replaced by the OH group-terminated moieties in the course of the reactions (Schemes 1, 2). The major peaks observed at 250°C on TGA plots of **3b**, **3f**, and **3g** show average weight losses of 20%, 35%, and 22%, respectively. Assuming that this weight loss is due to elimination of OH group-terminated moieties, the degree of sidewall functionalization in these derivatives can roughly be estimated as 1/25 in **3b**, 1/16 in **3f**, and 1/20 in **3g**.

[0055] The Raman spectra (Figures 1D and 3B) taken for residue materials after TGA of **3b** and **3g** derivatives, and prepared by different methods (Schemes 1, 2), both show a dramatic reduction in the intensity of the sp^3 carbon mode. This data indicates that the detachment of functional groups from nanotube sidewalls occurs in agreement with the previous observations of thermal degradation in other covalently functionalized SWNTs. See Khabashesku, V. N.; Margrave, J. L. *Chemistry of Carbon Nanotubes* in *Encyclopedia of Nanoscience and Nanotechnology*, Ed. S. Nalwa, American Scientific Publishers, 2004, Vol. 1, pp. 849-861, and references therein; Khabashesku, V. N.; Billups, W.E.; Margrave, J. L. *Acc. Chem. Res.*, 2002, 35, 1087; Bahr, J. L.; Tour, J. M. *J. Mater. Chem.* 2002, 12, 1952; Stevens, J. L.; Huang, A. Y.; Peng, H.; Chiang, I. W.; Khabashesku, V. N.; Margrave, J. L. *NanoLett.* 2003, 3, 331; Peng, H.; Reverdy, P.; Khabashesku, V. N.; Margrave, J. L. *Chem. Comm.* 2003, 362; Peng, H.; Alemany, L. B.; Margrave, J. L.; Khabashesku, V. N. *J. Am. Chem. Soc.* 2003, 125, 15174-15182.

[0056] The volatile species evolving during thermal degradation of SWNT derivatives have been analyzed by variable temperature pyrolysis-mass spectrometry (VTP-MS). The data obtained by VTP-MS for **3a-f** indicate a fragmentation of attached groups under vacuum conditions in the 300-550°C temperature range, detected in mass spectra by peaks at m/z 44 (C_2H_4O), 29 (HCO) in **3a** and **3d-f**, and additional groups of peaks at m/z 58,57,56,55 (C_3H_6O through C_3H_2O) and m/z 72,71,70 (C_4H_8O to C_4H_6O) in **3b** and **3c**, respectively. The presence of sidewall C-N bonded groups in the derivative **3i** causes the appearance of a major peak at m/z 105 due to detachment of diethanol amine at temperatures in the 250-400°C range.

c. Microscopy Analysis

[0057] TEM allowed direct imaging of sidewall modification in the hydroxyl nanotubes. FIGURE 10 shows a TEM image of glycerol functionalized SWNT **3f** specimen placed on lacey carbon-coated copper grid. The inset clearly shows a "bumpy" surface of a single nanotube resulting from covalent alteration of the fraction of carbon-carbon bonds on the sidewall from shorter sp^2 to a longer sp^3 state carbon formed linkages.

[0058] AFM studies of the **3f** derivative (FIGURE 11) revealed significantly reduced bundle sizes in comparison with the pristine SWNT nanotubes due to sidewall functionalization. The pristine SWNTs are known to aggregate into bundles ranging from several tens to a hundred nanometers in diameter. The average bundle sizes in **3f** were measured to be only from 3 to 6 nm in diameter. It is most likely that within those bundles the individual hydroxyl-nanotubes are linked together through hydrogen bonds formed by the terminal OH groups from the side-chains. Tapping mode analysis of the backbone profile of the functionalized SWNT bundles shows an average height of 4.4 nm. The height difference (~0.8 nm) measured along the backbone area, free of amorphous carbon particle impurity, likely relates to the approximate length of the $OCH_2CH(OH)CH_2OH$ chain attached to the nanotube sidewalls in a "stretched" fashion as shown by the TEM image in the inset on FIGURE 10.

Example 5

[0059] This Example serves to illustrate the improved dispersability or solubility the carbon nanotubes functionalized with hydroxyl-terminated moieties have in polar solvents—compared to unfunctionalized CNTs.

[0060] All of the hydroxyl-nanotube SWNT derivatives prepared in Examples 2 and 3 have shown an improved solubility in polar solvents compared with pristine SWNTs (FIGURE 12A). The most stable solutions were obtained from the glycerol-derived SWNT material **3f**, likely due to their possessing the highest content of hydroxyl groups in the nanotube side chain. The solutions of **3f** in water (~ 40 mg/L) were stable for several days, while ethanol solutions (FIGURE 12B) with higher **3f** concentration (~80 mg/L) showed little precipitation, even after several months.

[0061] All patents and publications referenced herein are hereby incorporated by reference. It will be understood that certain of the above-described structures, functions, and operations of the above-described embodiments are not necessary to practice the present invention and are included in the description simply for completeness of an exemplary embodiment or embodiments. In addition, it will be understood that specific structures, functions, and operations set forth in the above-described referenced patents and publications can be practiced in conjunction with the present invention, but they are not essential to its practice. It is therefore to be understood that the invention may be practiced otherwise than as specifically described without actually departing from the spirit and scope of the present invention as defined by the appended claims.